Living the Electronics Revolution: 60 Years of Fun with Radio

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“Radio” and Radio Frequency (RF) Engineering

What is it?

The design of radio transmitters and receivers – electronic devices that send and receive electromagnetic radiation.
For years, RF was considered a branch of magic!

We designed with slide rules and curves, followed by a great deal of cut and try in the laboratory. When a design finally worked, you were not sure why.

Now we have sophisticated computer aided design tools. When we design and build a radio, it usually works the first time.
How did I get into radio? Comics, science fiction, and books!

• A 1946 comic book about Donald Duck’s radar – I still have my “radar box,” where I put the money I was saving to buy a radar when they came on the market.

• Alfred P. Morgan’s *A First Radio Book for Boys*

• Early TV science fiction
I developed a lifetime fascination with how radio communication works – transmission over long distances without wires.

During my career radio and ECE have changed from a world of hardwired single-purpose stand-alone stationary analog systems designed by classical mathematical analysis to a world of mobile networked software-driven digital devices designed by simulation and numerical analysis.

This is the electronics revolution as I was fortunate enough to live it! Here is its story from my perspective.
When I started graduate school in 1963, I thought my research career would involve taking radios to new places (outer space!) using new frequencies and new electronic devices.

But the problems would remain the same – Make analog radios
• Smaller
• More efficient (i.e. longer battery life)
• Higher capacity

A network was either something like NBC or a bunch of police radios with a dispatcher.

But a series of unforeseen things happened!
My Subjective List of Unforeseen Things That Changed the World - 1

How we went from a world of hardwired single-purpose of stand-alone stationary analog systems designed by classical mathematical analysis to a world of mobile networked software-driven digital devices designed by simulation and numerical analysis:

<table>
<thead>
<tr>
<th>Starting Year</th>
<th>Technology Drivers</th>
<th>Consequences for ECE</th>
<th>Consequences for Radio</th>
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</table>
| 1963          | Discrete solid state analog devices | • Slow demise of vacuum tubes  
• Multiple low-cost active devices available to circuit designers | • Portable radios  
• Satellite communications |
| 1965          | Discrete solid state digital devices| • Digital computers became available to researchers  
• Numerical techniques solved previously unsolved mathematical problems  
• Simulation became available and accepted as a rigorous analytical tool  
• Decline in importance of math to ECE research | • Analytical basis for antenna design  
• Computer Aided Design (CAD) for RF |
| 1971          | Microprocessors and digital ICs     | • Demise of analog circuitry for most applications  
• Practical Digital Signal Processing (DSP)  
• Software rises from nothing to dominance | • Signal processing functions performed digitally  
• Digital waveforms replace analog |
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<tbody>
<tr>
<td>1973</td>
<td>Hand-held cell phone</td>
<td>• Portable devices becomes a driver of employment</td>
<td>• Rebirth of interest in RF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Demise of TEM transmission lines for information</td>
<td>• Hand-held devices rise to dominance</td>
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<td></td>
<td>Practical optical fiber cables</td>
<td>• Transmission bandwidth a decreasing limitation for information systems</td>
<td>• Demise of radio (including satellites) for long haul communications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cellular backhaul becomes practical and cheap</td>
<td>• Enabled wireless = short-distance radio</td>
</tr>
<tr>
<td>1982</td>
<td>TCP/IP</td>
<td>• Everything becomes networked</td>
<td>• Network considerations drive radio design</td>
</tr>
<tr>
<td>1990</td>
<td>GHz CMOS logic + all of the above</td>
<td>• “Dumb” digital circuitry running highly intelligent software</td>
<td>• RF functions performed digitally – Software Defined Radio &amp; Cognitive Radio</td>
</tr>
<tr>
<td>2000-12</td>
<td>Social networks, open source software, hobbyist electronics</td>
<td>• TBD</td>
<td>• TBD</td>
</tr>
</tbody>
</table>
The result of these developments is the convergence of information technology: from devices that are single-purpose, large stand-alone, and fixed in location to devices that are multi-purpose, hand-held, intensely networked, and portable.
Graduate School 1963-67

M.S. Thesis – *A Procedure for Selecting Germanium Transistors for Use in the Radiation Environment of Space*

Ph.D. Dissertation – *The Loop Antenna Loaded with Active Elements*

Coursework evenly divided between solid state electronics and electromagnetics. Ph.D. research was in numerical EM. For 80 years it had been impossible to solve analytically for the current distribution on any real antennas. Now numerical techniques and the availability of digital computers (“IBM Machines”) made it possible!

In the years following graduate school I published exactly one more paper in device electronics and one in numerical electromagnetics!
I joined VT in 1969 following service as an army officer.
In 2011-2012 we have 72 faculty + 4 open positions

+ 4 new assistant professors: Bostian, Shah, Stutzman, Yavin

28 names, 24 people actually present in 1969-70
Graduate Courses ~ 40

Electrical Engineering Courses (Graduate)

500
501
503
505
506
507
5012
5013
5014
5015
5016
5017
5018
5019
5020
5021
5022
512, 522, 532
513, 523, 533
514, 524, 534
515, 525, 535
516, 526, 536
517, 527, 537
518, 528, 538
519, 529
597
598
599
601
602
611, 621
799

ELECTROSTATICS MAGNETOSTATICS AND MAGNETODYNAMICS
ELECTRO-ACOUSTICAL ENGINEERING ADVANCED CIRCUIT ANALYSIS
ADVANCED SERVOMECHANISMS
OPERATIONAL CIRCUIT ANALYSIS GRADIENTS AND SURGES
TRANSIENT ANALYSIS OF SYNCHRONOUS MACHINES
INFORMATION THEORY ANALOG COMPUTER
ANALOG COMPUTER LABORATORY
ELECTRICAL ENGINEERING MATERIALS ELECTRONIC CIRCUITS
IMPEDEANCE MEASUREMENT RANDOM SIGNALS AND NOISE
DIGITAL POWER SYSTEM ANALYSIS SAMPLED DATA SYSTEMS
POWER SYSTEM STABILITY ELECTROMAGNETIC WAVES
CONTROL SYSTEM SYNTHESIS
NONLINEAR CONTROL SYSTEMS THEORY AND DESIGN OF DIGITAL MACHINES
SEMICONDUCTOR ELECTRONICS SYNTHESIS OF PASSIVE NETWORKS
ADVANCED ENERGY CONVERSION INDIVIDUAL STUDY
SPECIAL STUDY RESEARCH AND THESIS
OPTIMUM CONTROL SYSTEMS
STOCHASTICALLY EXCITED ELECTRICAL NETWORKS
COMMUNICATION SYSTEM DESIGN
RESEARCH AND DISSERTATION

External Research Funding

1969-70 $0
2011-12 $29,235,212
Enrollment Figures.  (x) indicates women included in count

Then

**ECE**
Graduate 39 (1)
Ph.D. 16
M.S. 23 (1)
**Undergraduate** 443 (5)
Senior 164 (2)
Junior 134 (2)
Sophomore 131
Freshmen 114 (1)

**VT** 10,352
Graduate 1,084
Undergraduate 10,352

Thanks to Tamara Kennelly, Univ. Archivist

Now

**ECE**
Graduate 496 (71)
Ph.D. 311 (39)
M.S. & M.Eng. 185 (32)
**Undergraduate** 677 (66)
EE 404 (46)
CPE 273 (20)

**VT** 30,936
Graduate 6,856
Professional 380
Undergraduate 23,700

Thanks to Cindy Hopkins, Mary Taylor and Sharon Shrader
These were the research tools we had in 1969-70.

1 Mb!
First Proposals
• Dielectric Rod Backfire Antenna
• Dielectric Rod Beacon Antenna

Written in response to Dept. Head mandate that every faculty member who wanted a raise should write a proposal.

Turned down by all recipients.

Lesson learned: *People won’t fund you because of the beauty of your mathematics. Your proposal must solve a real problem that they have!*
First Proposals
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But a NASA manager liked my proposal and invited me to work for him over the summer, saying he would fund me to work on a propagation project!
NASA Program in Millimeter Wave Satellite Communications

4 and 6 GHz satellite systems, built to distribute cable TV programming, were hugely successful – it was the era of big backyard satellite dishes.

4 and 6 GHz spectrum was full – expansion would come in the 10-30 GHz band.

Because of water’s high dielectric constant, rain drops are a significant fraction of a wavelength in size above 10 GHz. They attenuate and depolarize. Attenuation in dB/km ~ frequency and rain rate both raised to powers.

Characterize rain attenuation and depolarization to obtain needed information for design of future systems.
The First Experiment: A 17.65 GHz Terrestrial Link. ECE’s First Federally Funded Project.

First digital recording of propagation experiment data - Strip chart recorders had been the standard.
Transmitter

Switch

OMT

+ 45° polarization

-45° polarization
The Culprit!
The ground link led to many years of experiments with a variety of NASA and commercial satellites.
We obtained a lot of data like this sample.

Our measurements and models provided the basis for the link design of the 10-30 GHz systems that are in wide use today.
I took a year’s leave from research in 1989 and served as an IEEE Congressional Fellow, working in the office of Rep. Don Ritter (R-PA), an MIT Ph.D. in physical metallurgy and a former Lehigh professor.

Afterwards, VT thought I knew a lot about talking to politicians!
(Actually, they talk and you just listen!)
I developed a strong interest in the intersection of ECE and radio with business. It led to the formation of CWT and a valuable 10 year collaboration with faculty from Business and Geography.

This was the great dot com and telecom boom, when everyone wanted wireless!

We did a lot of work in developing fixed wireless technology, which was obviated by the desire for broadband mobile access and the ability to deliver it by OFDM.
Overall Objective: Develop a rapidly deployable high capacity backbone radio system bringing high speed Internet service to a disaster site.

Technical Challenges: find short-lived radio paths of opportunity and compensate for the shortcomings of these paths at both the radio and the network levels to deliver optimum performance.
Wireless LAN Technology at This Time

No OFDM
802.11 was a low-data rate intra-office system
Cell phones were barely 2G with at best Cellular Digital Packet Data.

The only way to get OC3 (155 Mbps) data rates was by using millimeter wave frequencies with QPSK modulation.

VT held 28 GHz LMDS licenses and had the needed equipment.
NSF Disaster Communications Project  1998

Overall Objective: Develop a rapidly deployable high capacity backbone radio system bringing high speed Internet service to a disaster site.

Technical Challenges: find short-lived radio paths of opportunity and compensate for the shortcomings of these paths at both the radio and the network levels to deliver optimum performance.
The radio must think for itself. Emergency responders emphatically do not want a radio that requires hands-on adjustment by an expert. They need a radio that is smart enough to find the best path of opportunity, configure itself and communicate, all with minimal human intervention.

My students concluded we needed a **cognitive radio** – radio engineering plus artificial intelligence.
I said no! Artificial intelligence has a history of hype followed by failure – it was for science fiction movies! I wanted something that would work!
But the students were right.

They ignored my protests and pulled me into an entirely new area of research – at a time when I could have coasted into retirement!

Working Definitions

Software Defined Radio – how the radio is constructed and controlled

Legacy radios – function is defined in hardware.

Software defined radios – function is defined by software.

Cognitive Radio – how the radio behaves

Fixed radios – set by operator

Adaptive radios – adjust themselves to accommodate anticipated events.

Cognitive radios – sense their environment and learn how to adapt.

An SDR is essentially a computer that generates and understands radio signals.

An image of a computer and a piano is shown to represent the difference between legacy and software-defined radios. Another image of a cognitive radio is shown to represent its ability to adapt to its environment.
Cognitive radio began with Joseph Mitola’s work in the late 1990’s, where he visualized cognition running in the application layer. Our work extended it downwards into the MAC and PHY layers. PHY = hardware settings. MAC=access to the radio spectrum.
A cognitive radio can be realized as a cognitive engine (intelligent software package) controlling a software defined radio platform.

CR reads the meters and turns the knobs.
CWT² Cognition Cycle with Two Loops

- **Inner loop:** Learning
- **Outer loop:** Recognition and Adaptation

Environment Observation

- Waveform
- User/policy
- Radio hardware

Scenario Synthesizing

Knowledge Base

- Reasoning

Case-based Decision Making

Performance Estimation

Link Configure Optimization

- WSGA
  - Initialization
  - Objectives
  - Constraints

Radio

- Practice

Radio Hardware

- Power
- Frequency
- Bandwidth
- FEC
- Modulation
- Pkt length

Environment awareness and evolving knowledge lead to optimal radio reconfiguration.
Cognitive Engine – Software Architecture

United States Patent 7,289,972

Cognitive Radio Engine Based on Genetic Algorithms in a Network
Our distributed cognitive architecture allows a cognitive radio to incorporate modules from any source.

The cognitive engine coordinates components to realize: sensing, learning, and optimization. It enables development of new components for testing and comparison.
First Working Cognitive Radio Prototype 2004

- Cognitive Radio Testbed Link
- Interferer Degrades Broadband Wireless Link
- WSGA evolves radio operation

<table>
<thead>
<tr>
<th>Interferer</th>
<th>Link</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx=11dBm</td>
<td>Tx=6dBm</td>
<td>Tx=16dBm</td>
</tr>
<tr>
<td>QAM 16</td>
<td>QAM 16</td>
<td>QPSK 4</td>
</tr>
<tr>
<td>Fibs 12</td>
<td>Fibs 22</td>
<td>Fibs 4</td>
</tr>
<tr>
<td>3/4 FEC</td>
<td>3/4 FEC</td>
<td>1/2 FEC</td>
</tr>
<tr>
<td>Freq=b-5</td>
<td>Freq=a-5</td>
<td>Freq=a-5</td>
</tr>
</tbody>
</table>

- Link quality of service (QOS) is restored.
Cognitive Radio Demonstration at DySPAN 2007

In-lab experiments in ISM band with three known and 1 random external interferers

By Tom Rondeau

CE 1

200 kHz QPSK

CE 2

Random external signal

Magnitude (dBm)

2410 MHz

2415 MHz

1 MHz QPSK

1 MHz OFDM
The VT Public Safety Cognitive Radio (PSCR)

Objective: To solve the interoperability problem by providing intelligent and affordable all-band all-mode radios that find and identify public safety networks and configure themselves to interoperate with them.

PSCR Capabilities:
- Recognize all public safety waveforms 50 MHz – 2.2 GHz
- Interoperate with all public safety radios
- Provide a gateway between incompatible networks
- Serve as a repeater when desired

Vehicular Version: 2009

Hand-held Version: 2010-2011

Long-term Concept: Universal Interoperability
VT Cognitive Radio Milestones

- 2002 Origination of Cognitive Engine concept
- 2005 Start of NSF and NIJ funding for cognitive engine radio development
- 2006 Start of DARPA WNaN funding
- 2007 Demonstration of working prototype *Public Safety Cognitive Radio*
- 2007 SDR07 Grand Prize for 2007 *Smart Radio Challenge* student competition
- 2008 Demonstrations at NTIA, DySPAN, SDR08
- 2010 CSERE modular cognitive engine developed
- 2011 Start of AF funding for integrating cognitive radio with autonomous vehicles
- 2012 Public Safety Cognitive radio running on Beagleboard and E100 delivered
Current Projects

- Integrating cognitive radio with autonomous vehicles
- Computational models for cognitive radio
- Evaluating cognitive radio performance
- Swarm intelligence for cognitive networks
This research was fun and led to many publications.
BUT the faculty, students and staff members I have worked with are the best part of all! They have taught me a lot – particularly the students!
Of all our activities, the results of teaching last the longest. Some of your former students may remember your teaching 30, 40, or even 50 years from now.
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